Management of Late Blight of Potato

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Additional information is available at the end of the chapter

Abstract

Potato (*Solanum tuberosum* L.) is the most important crop and *Phytophthora infestans* (Mont.) de Bary is the oomycete, which was responsible for infamous Irish potato famine during 1843–45 and it continues to cause worldwide devastation of the potato. Moreover, this disease is re-emerging in the forms of different genotypes and causes huge yield loss in the potato crop. The factors which are responsible for huge yield loss of potato are applied improper management strategies and pathogen behavior. Management strategies includes; forecasting, cultural, biological, varietal and chemical management. Forecasting is the better option for management of late blight, if accurately forecasted and promptly information reaches to the end users. As infected potato tubers cause the primary sources of infection in next season. The cultural practices will also helpful in reducing inoculum load and managing the disease. The host resistance is best option for management of this disease. However, due to very divers' virulence nature of *P. infestans;* the resistance of the varieties is wiped out within a decade. Several fungicides including contact, systemic and translaminar have been evaluated from time to time; however, the pathogen has shown a remarkable capacity for change with respect to host genotype and fungicides. Nowadays biological control is gaining importance due to its eco-friendly in nature.

Keywords: potato, late blight, disease, management, fungicides, *Phytophthora*

1. Introduction

The Potato was originated in the hills of Andes and Bolivia in South America, subsequently it was introduced into Europe by Spaniards in the second half of the 16th century, from there it spread throughout Europe and rest of the world in the mid 17th to mid of 18th century. In Asia, particularly in India, it was introduced by Portuguese in 17th century [1]. The late blight fungus co-evolved with potato in Central and South America and subsequently spread

to other parts of the world mainly through infected seed tubers. The late blight disease caused by oomycete, which was initially reported as *Botrytis infestans* in 1845 by C. Montagne, later on German scientist Anton de Bary renamed as *Phytophthora infestans* (Mont.) de Bary [2]. The entire potato crop across Europe, especially in Ireland, was killed prematurely during 1844–45; leading to worst ever famine the 'Irish Potato Famine' [3]. One million people died of starvation due to that famine and another million migrated to the USA and other parts of the world.

The late blight disease was recorded in India for the first time between 1870 and 1880 in the Nilgiri hills [4]. Under subtropical plains particularly in eastern part of the India, it was first observed in 1898–1900 in Hooghly district of West Bengal [5]. In the northern part, it appeared for the first time in 1883 in Darjeeling and subsequently spread rapidly to other adjoining hills [6]. The late blight disease was observed in Khasi hills (North-eastern Region) in 1885, Kumaon hills in 1897 and in Shimla hills (North-western Region) in 1902 [5, 7]. During 1913, it appeared at several places in Assam and Bihar [6, 8–11]. In plains of Uttar Pradesh, it was reported for the first time in 1943 in Dehradun and Meerut [10]. Severe attack of the late blight was observed in Meerut district in 1949, 1950 and 1951 and subsequently in many other districts of Uttar Pradesh [12]. In Punjab, the disease was occurred annually from 1958 to 1963 except during 1961 [13]. Potatoes had been grown in Mahabaleshwar hills and other parts of Maharashtra but late blight was observed there only in 1973 [14]. In Gujarat and Madhya Pradesh, the disease was observed in traces in 1968 and in Rajasthan in 1958 [12]. Afterwards, appearance of late blight disease is regular feature with high disease severity in hill areas while in plains disease severity is moderate to high level.

2. Crop losses

Phytophthora infestans causes late blight diseases in potato and tomato crops worldwide. It is not cause only economic losses of yield but also the quality and quantity of the crop. It is a highly researchable pathogen in plant diseases. The worldwide late blight disease is re-emerging, therefore this disease is constantly observed by the late blight researchers [15]. The late blight disease is considered emerging disease, it is not only having important in global crop production, but also pose severe risks on a local level, especially on small farms in developing countries [16]. The losses caused by late blight disease, it varied countries to countries, as per their adopted plant protections measures and grown cultivars. The yield losses due to late blight of potato were reported up to 50–70% during the 2007 under favorable environmental condition in Pakistan [17]; however recently Ahmed et al. [18] reported that late blight can induce 100% yield loss under epidemic condition in Pakistan. As far as Indian scenario is concerned, reduction in potato production due to late blight ranged between 5 and 90% depending upon climatic conditions, with an average of 15% across the country [19]. However, recently yield loss was reported, overall basis a range of 10–20% due to late blight in the year 2013–2014 major potato growing sites of the India viz., Uttar Pradesh, West Bengal, Punjab, Karnataka and Uttarakhand [20]. Whenever, disease appeared in epiphytotic form at early stage of the crop yield loss would be more. Tuber yield decline was significantly higher in unmanaged crop, which could go as high as 90% of total productivity in hilly regions. The changing climate pattern is being influenced appearance of late blight as it is occurring every

year in plain region with moderate to high disease severity. Variations in disease severity are mainly due to climatic factors i.e. rainfall, relative humidity, temperature and pathogen virulence. In Punjab (main potato growing belt), severe epidemics of late blight disease have appeared during 1985–1986, 1989–1990, 1992–1993 and 2006–2007 [21]. In 2006–07, average crop loss of 22% in productivity resulting in a net loss of around 0.16 mt of potato in the state of Punjab alone. The increase in disease severity could be due to a change in the pathogen population [22]. The varying degree of crop losses was also reported due to late blight from Punjab, Haryana, UP, Maharashtra Karnataka, Bihar and West Bengal [23]. The decline in productivity and yield of potato was in between 25 and 85% due to late blight, depending mainly on degree of susceptibility of the host plant [24]. The economic costs associated with late blight to be somewhere around US $3–5 billion per year was estimated by several authors [25, 26]. A method had been used to conservative estimate costs of late blight and it was observed that lowest yields mainly in developing countries and previous eastern block countries which suffered over €10 billion per annum at least, whereas in developed countries with high yields (7.5% of global potato production) suffered damage of about €1 billion per year [27].

3. Symptomatology

The late blight disease affects all plant parts especially leaves, stem and tubers.

3.1. Leaves

Pale green water soaked spots (2–10 mm) appear mostly on the margin and tips. In moist weather, spots may appear anywhere on the leaves, enlarge rapidly and turn necrotic and black killing the entire leaf instantly. On the corresponding lower side, whitish cottony growth containing millions of sporangia forms around the dead area in a ring pattern (**Figure 1**).

3.2. Stem and petiole

Light brown lesions develop which elongates and encircles the stem and petioles breaking them and killing the plant/leaves instantly. Stem infection is more severe under high temperature and relative humidity conditions (**Figure 2**). Symptoms of stem blight are observed more in last ten years.

3.3. Tubers

Rusty brown discoloration of the flesh is the typical symptom of late blight (**Figure 3**). On outside tuber surface, hard depressions with purplish tinge on the sides are a common feature. Normally, late blight infected tubers are hard but associated secondary pathogens may set in soft rot symptoms.

3.4. Field infection

Generally, late blight appears on lower most leaves of the plant which goes unnoticed from a distance. Slowly, the disease spreads to the middle and then upper leaves. Subsequently it

Figure 1. Whitish cottony growth on the lower surface of leaf.

Figure 2. Late blight symptom on potato stem.

Figure 3. Late blight symptom on potato tubers.

Figure 4. Late blight affected potato field.

spreads whole plants and near of the plants. The disease spreads faster and the entire crop gets killed as if burnt by fire (**Figure 4**). The heavily infected field gives fetid odor which can be felt from a distance.

4. Disease epidemiology

The late blight infected tubers are the major sources to cause the infection. Moreover, refuse piles and volunteer plants also serve as primary source of disease particularly in the hilly

region. Wherever, both mating type is existed oospore formation take place and oospore also has the potential to cause and initiate the disease. The spores germinate and infect the exposed tubers. Although, some of the infected tubers get completely rotted by the time, crop is harvested but, still lot of tubers carry incipient infection, and escape in the cold store/country store where they remain dormant but alive. These tubers if used as seed, becomes the source of infection of the disease in the next crop season [28]. Sporangia are formed wide range of temperature (3 to 26°C) and optimum is 18–22°C. The sporangia are germinated by two ways process i.e. indirect and direct germination. It depends mainly on temperature. Indirect germination generally occurs at temperatures of 6 to 15°C (optimum 12°C) by means of sporangia produces zoospores. Direct germination takes place under warm temperature and a range of 4 to 30°C (optimum 25°C). High relative humidity (>90%) is required for spore formation, germination and infection; whereas >80% is essential for lesions expansion. Extreme light is harmful for *P. infestans* and sometimes sporangia may be killed due to extreme light. Cloudy weather is favorable for late blight. The cool (12–15°C) and high humidity (>90%) weather with heavy dews or rains alternating with warm (18–20°C) moist period favor for rapid development of disease. Infection and disease development is observed a range of 7.2–26.6°C [29].

5. Management

Several management strategies have been developed for late blight of potato and adopted by the farmers/potato growers as per availability of the resources. Amongst them chemicals, host resistant, biological control, cultural control are discussed below:

5.1. Chemical management

Chemical management is very popular strategy for the management of late blight. Since the discovery of Bordeaux mixture in 1885 and it was first important landmark in the history of chemical disease control. Bordeaux mixture belongs to first generation of fungicides along with other inorganic chemicals. After more than 130 years, the introduction of Bordeaux mixture (Copper sulfate, hydrated lime and water), large numbers of fungicides (first generation Bordeaux mixture to fourth generation Mandipropamid & Azoxystrobin) were evaluated at worldwide against late blight of potato/tomato. In practice, the traditional management of late blight depends highly on preventative fungicides, application on a regular calendar basis (e.g. weekly) during the growing season [30]. The population diversity and disease incidence of *P. infestans* has been increased through the development of systemic fungicide resistance (insensitivity) and the transcontinental shipment of the late blight infected potato tubers and tomato plantlets [31]. Metalaxyl fungicide which comes under Phenylamide group with FARC 4, was introduced against oomycetes, very effective for late blight management and highly adopted worldwide. However, after introduction within three years metalaxyl resistant isolates were detected on field grown potatoes in Ireland, The Netherlands and Switzerland [32]. The site-specific systemic fungicide, mefenoxam (the active isomer in metalaxyl), inhibits sporulation and mycelial growth inside host tissues by specifically inhibiting RNA polymerase-1, a mutation that changes the affinity of target sites could easily lead to fungicide resistance [33]. In Indian scenario, metalaxyl based fungicides were

introduced on experimental basis for management of late blight during late 1980's however, their commercial use started only during 1994–1995 [34]. In India, 200–400 ppm tolerance level was observed with metalaxyl. After 12 years, its introduction during 2006, the metalaxyl based fungicides failed to protect the potato crop from the late blight in temperate highlands leading to 40–70% crop losses. Systemic fungicide metalaxyl is cause of concern for management of late blight disease due to quickly developed resistance. Pathogen had developed.

Tolerance up to 400 ppm and genetic studies crosses indicated that a semi dominant major locus determines resistance to metalaxyl, since insensitive and sensitive parents usually yielded progeny with those phenotypes at a 1:1 ratio [35, 36]. The heterothallic single mating type isolates of *P. infestans* was exposed to 9 of the 11 commercial fungicide formulations for assess their effect on formation of oospores. The highest numbers of oospores were observed on media amended with Ridomil 2E (metalaxyl) and Ridomil Gold EC (mefenoxam) at 0.1 to 10 μg a.i./ml, when averaging it was found that 471 and 450 oospores/petri dish, respectively. The remaining fungicides viz., Maneb, Manzate (Mancozeb), Curzate (cymoxanil +mancozeb), and Acrobat MZ (dimethomorph + mancozeb) also induced oospore formation, which ranged from 0 to 200 oospores/petri at fungicide concentrations from 0.1 to 10 μg a.i./ml. No oospores were formed on media amended with Bravo (chlorothalonil) or Tattoo C (chlorothalonil + propamocarb HCl), moreover both the compounds completely suppressed growth of the isolates at 0.1 and 1 μg a.i./ml. The metalaxyl resistant isolates formed oospores in response to the fungicides more often than the metalaxyl sensitive isolates [37]. Metalaxyl + mancozeb (Ridomil MZ) and ofurace (Orafce 50WP) were reported to provide highly effective control of late blight [38]. The fenamidone is a novel fungicide, which acts on cytochrome bc1 in mitochondrial complex III of *P. infestans* at a number of points in its life cycle [39]. Cymoxanil based fungicides possess a novel mode of action by preventing electron transfer between cytochrome b and c1 in mitochondrial complex III and provide good scope for the control of late blight of potato and tomato [40, 41]. Efficacy of seven fungicides was tested under *in vitro* conditions and the fungicides, which showed promising results, were further evaluated under field conditions and fenamidone based fungicide was found most effective in controlling late blight followed by cymoxanil based while mancozeb was found least effective; similarly the systemic fungicides viz., fenamidone and dimethomorph were reported most effective *in vitro* for management of late blight [42, 43]. Various studies showed that a reduced use of fungicides lowers the selection pressure for mefenaxam-resistant strains and mixture with a contact fungicide improves efficacy and may slow the development of resistance to mefenoxam [44, 45]. The systemic fungicides have better persistence on the host surface and are being used as mixture with contact fungicides against late blight so as to avoid development of resistance in pathogen [46]. The fungicide mixtures, containing two or more fungicides with different modes of action, have been developed with the twin objectives of broadening the activity spectrum against diverse plant diseases and to check the development of resistance in the target pathogens [47]. In commercial production of potato is not viable without fungicides for management of late blight. Fungicide mixtures and targeted application based on late blight forecasting model are very important for managing late blight. However, due to delisting of many fungicides products under the EU Pesticide Directive and environmental concerns, provides impetus for potato breeding and more effective fungicide application [48]. It has been reported from European country that the same fungicide should not applied more than two sequential

applications [49]. The severe late blight can be effectively managed with prophylactic spray of mancozeb at 0.25% followed by cymoxanil+mancozeb or dimethomorph+mancozeb at 0.3% at the onset of disease and one more spray of mancozeb at 0.25% seven days after application of systemic fungicides in West Bengal [50]. Similarly, one spray of mancozeb followed by three spray of cymoxanil + mancozeb was effective on cv. Kufri Bahar under western UP [34]. Due to development of resistance to fungicides, a new fungicide, Victory 72 WP was first used in controlling late blight of potato and tomato in West Shoa of Ethiopia [51]. The late blight specific spray scheduling method and a method of scheduling sprays for both diseases (early and late blight) suppressed early and late blight as well as did weekly sprays (conventional methods) and with the same average number of applications as with weekly sprays [52]. The customarily, spray schedules were one prophylactic spray using contact fungicides followed by systemic fungicides and one more spray of either same contact or same systemic fungicides. A unique combination of treatments was developed keeping in view the sensitivity of *P. infestans* to develop fungicide resistance. The post spray (curative spray) of same mode of action fungicide was not taken. Prophylactic sprays of chlorothalonil/mancozeb followed by systemic/ trans laminar fungicides were found effective than post symptom sprays. This will be useful to minimize the yield losses due to late blight and assist in reducing development of resistance against fungicides in pathogen [53]. The spray schedule of mancozeb 75% WP (0.2%- before appearance) followed by two more spray with mancozeb 75% WP (0.2%) + dimethomorph 50% WP (0.2%) at 7–10 days intervals showed less terminal disease severity (24.55%) with highest disease controlled (74.45%), which was at statistically par with treatment mancozeb 75% WP (0.2%, before appearance) followed by cymoxanil 8% + mancozeb 64% WP (0.3%) with two more spray at 7–10 days intervals, with 27.56% terminal disease severity along with disease controlled 71.29%. One spray of mancozeb (contact fungicides: before appearance) and latter two more sprays of translaminar/systemic + contact fungicides at 7–10 days interval give better results for managing late blight of potato [54]. The highest marginal benefit was achieved by applying first Ridomil then Dithane M-45 at 14–21 days interval. The lowest marginal benefit was with alone application of Ridomil at 21 day spray interval. At 7 days sprays was more economical to apply Dithane M-45 than Ridomil first followed by Dithane M-45 subsequently [55]. Twelve fungicides were evaluated on isolates of three identified clonal lineages (US-22, US-23, and US-24) of *P. infestans* using a detached tomato leaf assay in preventative and post-infection methods. The results revealed that these fungicides were suitable in conventional and organic systems, which can effectively control late blight caused by new clonal lineages of *P. infestans* when applied preventatively and late blight caused by the US-24 clonal lineage may require less fungicide than US-22 or US-23 to manage the disease [56]. The efficacy of Ametoctradin 27% + dimethomorph 20.27% (w/w) as a new molecule for management of late blight of potato was reported in India [57]. Initium (ametoctradin) is a new fungicide for management of *Phytophthora infestans*. It affects mitochondrial respiration inhibitor interfering with the complex III (complex bc1) in the electron transport chain of the pathogen, thus ATP synthesis in the fungal cells is inhibited. It is a non-systemic fungicide that remains primarily on the leaf surface where it is adsorbed with high affinity to the epicuticular wax layer of the epidermis [58]. Many oomycete-specific fungicides such as QoI compounds, dimethomorph, propamocarb, etc. [59] were commercialized, but currently, we are unaware of any fungicide that could effectively halt epidemics caused by metalaxyl-resistant strains under conditions favorable to *P. infestans* growth and development [60]. Isolates of *Phytophthora*

infestans showed 10-fold or more variation in baseline sensitivity to many fungicides including cymoxanil, dithiocarbamates, mandipropamid, and strobilurins [61–63]. Various substances other than fungicides also were tested for management of late blight of potato. Ammonium molybdate, cupric sulfate and potassium metabisulfate at 1 mM partially inhibited the growth and spore germination of *P. infestans*, whereas ferric chloride, ferrous ammonium sulfate and $ZnSO_4$ at 10 mM completely inhibited growth and spore germination [64]. The foliar spray of $ZnSO_4$ and $CuSO_4$ (0.2%) micronutrients, 12 days delayed the onset of late blight when used with host resistance, subsequently reduced disease severity with higher yield [65]. Sub-phytotoixc dose of boron with reduced rate of propineb + iprovalidicarb has been found more effective than treated with fungicides alone [66]. β-aminobutyric acid (BABA) has been known as an inducer of disease-resistance. However, only the R but not the S enantiomer of BABA primes for resistance. Unfortunately, BABA can also impose growth stress in some treated plants therefore BABA analogs with reduced stress effects are highly desirable for agricultural field [67]. Plant activator viz., BABA and phosphoric acid was evaluated against late blight by various researchers with combination of fungicides or alone [68–71]. A 20–25% reduction of the fungicide dose in combination with BABA gave on average the same result on late blight development as full dose Shirlan alone in field condition, while reduced dose of Shirlan alone sometimes resulted in less effective protection. However, *in vitro* results indicated that the efficacy was lasted for only 4–5 days after BABA treatment and subsequently efficacy was lowered. The partially resistant cultivars Ovatio and Superb reacted to lower concentrations of BABA where no effect was found in susceptible cv. Bintje [72]. Two SAR activators (BABA and phosphorous acid) were found effective against late blight of potato with significantly reduced disease severity (40–60%). The expression of the defense related genes and *P. infestans* effecter proteins β-1,3 glucanase, PR-1 protein, *phytophthora* inhibitor, protease inhibitor, xyloglucanase, thaumatin protein, steroid binding proteins, proline, endochitinase and cyclophilin genes were up regulated with the SAR activator treatment compared to unsprayed [73]. Since last one and half decades, various fungicides have been developed for management of late blight. Isolates of *P. infestans* might develop resistant over the period. Fungicides resistance with currently used fungicides, including dimethomorph, has been reported [74, 75]. There are three key phases in the development of fungicide resistance (i) emergence, (ii) selection, and (iii) adjustment. In emergence, the resistant strain has to arise through mutation and invasion whereas in selection, the resistant strain is present in the pathogen population and a small portion of the pathogen population carrying the resistance increases due to the selective pressure imposed by the fungicides. In case of adjustment phase, the resistant fraction of the pathogen population has become large, crop managers have to adjust fungicide programs, by changing the dose or active substance(s) used, in order to maintain control [76].

5.2. Biological control/eco-friendly management

Generally, management of late blight by eco-friendly means is a difficult task particularly when the level of disease pressure is high along with prevailing congenial environmental condition. However, due to negative impact of chemicals on environment as well as human health, nowaday's eco-friendly management is gaining more importance. Management of late blight through eco-friendly way, using botanicals has been initiated in European and American countries during the last years of 20th century [77, 78]. Out of 100 species in 54 plant families tested against

P. infestans, the leaf extracts from onions, garlic, *Malustoringo*, *Reynoutria japonica* and *Rheum coreanum* revealed positive inhibition of mycelial growth of *P. infestans*. *M. toringo* extracts strongly inhibited *P. infestans* and was effective in managing late blight also [79]. The effectiveness of some antifungal compound was reported against late blight from botanicals [80]. The antagonist *Bacillus subtilis* B5 was found effective in inhibiting the growth of *P. infestans* [81]. The efficacy of bacterial and fungal antagonist found effective as lowest average disease severity (27.89%) was recorded in treatment when *Bacillus subtilis* (B5–0.25%) + *Trichoderma viride* (TV-0.7%) was applied before disease appearance followed by cymoxanil 8% + mancozeb 64%WP (0.3%) at onset of late blight and one more spray of B5 + TV after 7 days [82]. The different isolates of *Trichoderma* were evaluated against *P. infestans* and found that *Trichoderma* isolates HNA 14 was most effective under both laboratory and field conditions and showed mycoparasitism against *P. infestans* when observed under scanning electron microscope [83], whereas *T. koningiopsis* and *T. asperellum* were effective against *P. infestans* under both laboratory and field conditions [84]. Rhamnolipid bacterial based formulation (0.25%) was tested under field trials at three different locations for managing late blight of potato. It was observed that the terminal disease severity in rhamnolipid formulation sprayed plot was 45% (against control plot 100%), 47.5% (against control plot 92.5%) and 59.2% (against control plot 76.64%) at Modipuram, Lawar (Meerut) and Jalandhar, respectively [85]. The some phyllospheric microorganisms *viz.*, yeasts *Sporobolomyces* spp., *Acetenobacter* spp., isolates of *Pseudomonas* spp. and *Bacillus* spp. were reported antagonistic to *P. infestans* [86, 87]. The *Bacillus* sp. inhibited mycelial growth of 7 plant pathogenic fungi *in vitro* and *in vivo* and the same bacterium protected tomato plants against *P. infestans* [88]. A bacterium (*Serratia* sp.), and 4 fungi (*Trichoderma* sp., *Fusarium* sp. and 2 *Penicillium* spp.) were tested against *P. infestans* on tomatoes under field conditions and found that *Penicillium* reduced the lesion area/plant between 8 and 40% [89]. One hundred twenty two microorganisms isolated from the phyllosphere of potatoes on the development of *P. infestans,* 23 effective microorganisms (spore-forming and non-spore-forming bacteria, yeasts and fungi) were tested in dual cultures and different patterns of inhibition of *P. infestans* were observed [90]. Various naturally occurring microorganisms, i.e., *Trichoderma viride, Penicillium virdicatum, P. aurantiogiseum, Chetomium brasilense* [91], *Acremonium strictum* [92], *Myrothecium varrucaria* and *Penicillium aurantiogriseum* [93] showed antagonistic effect against *P. infestans*. The antagonistic activities of *Pseudomonas fluorescens, Pseudomonas* sp., *Aspergillus flavus, A. niger, Penicillium* sp., *T. virens* and *T. harzianum* were tested *in vitro* conditions against *P. infestans, Fusarium sp.* and *Rhizoctonia solani.* All bio-agents inhibited the mycelial growth of the pathogens in comparison to control [94]. The defense enzymes viz., chitinase and β.1, 3-glucanase activities of *B. subtilis* and *T. harzianum* were well reported against late blight of potato and early and late blight of tomato [95, 96]. Forty-three bacteria were isolated from the phylloplane and rhizosphere of potato and canola plants, evaluated against *P. infestans* causing late blight on potato. It was reported that more than one system (*in vitro* culture media, detached leaves, and whole plants) should be used for selecting and identifying potential of bioagents [97]. A well-known group of microorganism used is the fluorescent *Pseudomonas* which excretes secondary metabolites including antibiotics and biosurfactants that are inhibitory to plant pathogens [98]. Naturally occurring surface active compounds derived from micro-organisms are called biosurfactants. These are amphiphilic biological compounds produced extra-cellularly as part of the cell membrane by a variety of bacteria, yeast and fungi [99]. Biosurfactants can be used as alternatives to chemical surfactants as their capability of reducing surface and interfacial tension with low toxicity,

high specificity and biodegradability make them important for inhibiting pathogens. The best antagonistic activity against *P. infestans* is observed in the genera of *Pseudomonas* and *Bacillus* as they produce wide range of antibiotics and biosurfactants and can be used as alternatives to chemical surfactants [100]. The metabolite of biosurfactant producing bacterium, *P. aeruginosa* has shown high efficacy against *P. infestans* under *in vitro* conditions [101]. Ninety five isolates of bacteria were evaluated for their biosurfactant as well as biocontrol activity against *P. infestans*. It is observed that only 15.8% isolates showed biosurfactant activity and only five isolates were found effective against *P. infestans* for biocontrol properties [102].

5.3. Cultural practices

The cultural practices, includes inoculum free seeds and planting materials, crop and field sanitation and adjustment of crop cultures. Cultural practices classified into three categories: i. Practices, which are usually applied for agriculture purposes not directly connected with crop protection, such as fertilization and irrigation. They may or may not have a positive or a negative side effect on disease incidence or severity, ii. Practices that are used completely for disease control, such as sanitation and flooding and iii. Practices, which are used for both agricultural purposes and for disease control, such as crop rotation, grafting and composting [103]. Late blight of potato can be managed up to some extent using cultural practices. The infected potato tubers are the primary source of inoculums for causing initial infection of late blight. Besides, areas wherever both mating type (A1 & A2) are co-existed, oospore formation takes place and a possibility to survive longer period in the soil and cause the infection from soil sources also. The oospores as soil-borne inoculums and its significant are determined by formation of oospore in plant tissue and their survival in soil. There is a clear cut correlation between crop rotation and early infections of late blight disease. Generally, infection starts early in fields which are not used for crop rotations. The decline in early infection was most pronounced in fields subjected to crop rotations for three or more years between the potato crops [104, 105]. It might be a reason that inoculums are less survived in non-crop rotation field than the crop rotated fields. It is clearly indicated that practices of crop rotation is an important aspects for reducing the risk of soil-borne infections of *P. infestans*. The date of potato planting is also useful to avoid the late blight of potato, especially by changing in planting dates. On average, planting in the last 10 days of September resulted in less severe late blight epidemics [106]. Mixed cropping, barrier crops and strip cropping are also helpful for reducing disease severity of potato late blight. Concept of mixed cropping and barrier crops were investigated for managing/delaying the spread and build up of late blight in western Uttar Pradesh at Meerut. Results revealed that spreads of the disease were delayed by 7 days by planting resistant cultivars in alternation with susceptible one whereas barrier crop (oat) delayed the spread of disease by 4 days [107]. Strip cropping of potatoes significantly reduced late blight severity in organic production when the crop was planted perpendicular to the wind neighbored by grass clover [108]. Control of contaminated sources such as infected tubers, volunteer plants, waste heaps, disease in neighboring fields and re-growth after haulms destruction can help in management of the disease [109]. It has been assessed that onset of epidemic can be delayed by 3 to 6 weeks if all primary infection from early potato can be eliminated. It has been shown that during most years late blight epidemics start from infected plants on dumps [110]. Covering of dumps with black plastic sheet throughout the season and preventing seed tubers from

becoming infected is an important step to reduce the primary inoculum [111]. Avoiding use of excess nitrogen and use of moderate nitrogen fertilization is often recommended as cultural practices to delay the development of late blight [112]. Higher dose of phosphorus and potassium has been found to give a higher yield in a late blight year [113]. The selection of suitable cultivars with late blight resistant, well aerated fields, pre-sprouting of tubers and early planting are some of the measures for foliar blight while planting potatoes on large steep ridges, right time of mechanical weeding and harvesting, avoiding rapid shift of harvested tubers or long transports could minimize tuber blight [114].

5.4. Host resistance

Host resistance is the best option for management of late blight of potato and it is eco-friendly in nature. Generally, after a decade, resistant level of the cultivars is being defeated, due to matching of new virulence genes. To find out the source(s) of resistance to late blight in potato was serious concern after Irish famine, during late 19th century. The fact that *P. infestans* originated in Mexico where lots of wild *Solanum* species also grow and co-exist with late blight led to the belief that wild *Solanum* species would possess a fair degree of resistance to balance the *Phytophthora* attack. In India, selection of late blight resistant genotypes dates back to 1936 when potato germplasm was screened in the field. In subsequent selections, clones of *S. demissum* and *S. antipoveizii* were found immune and later used as parents for late blight resistance breeding. Development of resistant cultivars and exploitation of screening methodology has played an important role in the management of late blight [115–120]. CPRI has released varieties having moderate to high degree of resistance to late blight for cultivation both for plains and hills. Some of them are Kufri Giriraj, K. Shailja, K. Himalini and K. Himsona (for hills) and K. Pukhraj, K. Anand, K. Sutlej, K. Badshah, K. Arun, K. Jawahar, K. Garima, K. Chipsona-1, K. Chipsona-2, K. Chipsona-3 and K. Frysona (for plains). Advanced hybrid MS/99–1871 derived from cross PH/F-1045 X MS/82–638 has been released for commercial cultivation under the name Kufri Garima. Foliage resistance of advanced hybrids tested under laboratory and field conditions did not establish close relationship. The expression of late blight resistance in foliage and tuber were not related [121]. K. Mohan is a new variety with field resistance to late blight reported [122]. Recently, Payette Russet: a dual-purpose potato cultivar with late blight resistance (both tuber and foliage) and high resistance to potato virus Y released in USA [123]. Somatic hybrids having high degree of resistance to late blight can be used as one of the parent for potato breeding [124]. The somatic hybrids P4, P8 and P10 reported for the introgression of important characters such as high tuber dry matter concentration, resistance to late blight into the cultivated potato via conventional breeding methods for cultivar development in the sub-tropical plains of India [125].

5.5. Forecasting models

The late blight pathogen is highly dependent on the environmental factors like temperature, relative humidity and leaf wetness etc. for causing late blight disease. Therefore, various forecasting model had been developed for forecasting late blight disease. Initially, Van Everdingen [126] evolved 'Dutch rules' for predicting the initial occurrence of late blight and for scheduling fungicide applications under Holland condition. Subsequently, Beaumont's period [127];

Irish rules, moving day concept [128]; severity value accumulation [129]; negative prognosis [130] and mathematical based models were developed worldwide. Large number of forecasting systems like BLITECAST, SIMCAST, ProPhy, PROGEB, PhytoPre, NegFry, Web-Blight, Plant Plus, PhytoPRE + 2000, China Blight, Bio-PhytoPre etc. have been developed for different regions of the world [112]. International Potato Centre has linked two disease forecasting models, Blitecast and Simcast to climate database in a Geographical Information System (GIS) to estimate global severity of potato late blight. Using GIS database, they suggested that an increased access to host resistance and fungicides in developing countries could have a strong economic impact on potato production [131]. A web-based Decision Support System (DSS) was developed for management of potato and tomato late blight [132] which links various models into a system that enables prediction of disease dynamics based on weather conditions, crop information, and management strategies. Growers identify the location of their production unit of interest and the system automatically obtains observed weather data from the nearest available weather station, and location-specific forecast weather data from the National Weather Service – National Digital Forecast Database [133]. Recently a new forecasting model BLITE-SVR developed for prediction of first appearance of late blight of potato. A total of 13 kinds of weather data had been utilized for development of this model and performance of BLITE-SVR compared with the conventional moving-average method as well as through pace regression and linear regression. The accuracy of prediction was 64.3% by BLITE-SVR, with 42.9% by the conventional moving-average method, 42.9% by pace regression and 35.7% by linear regression for first appearance of late blight of potato [134].

In Indian scenarios, a forecasting model has been developed for Darjeeling hills utilizing 12 years rainfall data on the concept of Cook's moving graph and Hyre's [135]. Another forecasting model had been developed using daily weather data (temperature, rainfall and RH) for actual appearance of late blight for Shimla, Shillong and Ootacamund [136]. The computerized forecasting model 'JHULSACAST' developed for western UP for both the rainy and non-rainy conditions and it is being utilized for forecasting of first appearance of late blight in the regions and large scale of farmers are benefited by timely adopting control measures [137]. The wireless sensor network was used for validation of 'JHULSACAST' with other forecasting late blight models in western Uttar Pradesh using human participatory sensing approach. It was observed that the 'JHULSACAST' has been found to be significantly accurate than the Ullrich, Fry, Winsteland Wallin models for the Hapur region of Uttar Pradesh, India [138]. JHULSACAST model template was used for calibration for development of forecasting models for Punjab [139], Tarai region of Uttarakhand [140] and plains of West Bengal [141]. A decision support system also developed for assisting in management of late blight by ICAR-CPRI, which includes three modules i.e. i) decision rules for forecasting first appearance of late blight in plains during rainy and non-rainy years based on temperature, relative humidity, and rainfall data, ii) decision rules for need based application of fungicides, and iii) regression models for yield loss assessment. All these modules have been combined and a web based decision support system for western Uttar Pradesh has been developed and hosted on ICAR-CPRI server. The yield loss assessment model was developed using two parameters *i.e.* per cent yield loss as a dependent variable and AUDPC as an independent variable. Twenty five linear and non-linear regression lines were fitted with three years data and amongst best non-linear reciprocal hyperbola regression line, which has $R^2 = 0.84$ was selected. Further, this model was validated and results revealed that the

deviation from 0.5 to 13.70% in 2010–2011, 1.16 to 9.69% in 2011–2012 and −3.01 to 9.23% in 2012–13 between actual and predicted yield loss [142]. Recently, INDO-BLIGHTCAST- a web based Pan-India model for forecasting potato late blight which is an improvement over JHULSACAST has been developed. It predicts late blight appearance using daily mean temperature and relative humidity data available with meteorological stations and does not require hourly weather data, not region/location specific and can be used across the country without any calibration [143]. An algorithm to determine the severity of potato late blight was developed using image processing techniques and neural network. The proposed system takes images of a group of potato leaves with complex background as input which are captured under uncontrolled environment [144]. It could further modified for spray of fungicides based on disease severity. Thus, the disease forecasting model is not only forecast for initial appearance of late blight but also assist in managing the late blight with proper spray schedules.

6. Conclusion

Late blight disease could be managed by taking in account all available resources i.e. chemical, host resistant, cultural or biological in the form of integrated disease management. Although the chemical and varietal management are being used widely all over the world, biological control could be used especially in organic potato cultivation or reducing the number of fungicides sprays/objectives to less use of fungicides. It is cause of concern wherever, oospores are survived and emergence of new strain/re-emerging the late blight. It will in future line of action that how disease is re-emerging and how to manage at short span after its re-emerging.

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